

Mid-century emission pathways in Japan associated with the global 2 °C goal: national and global models' assessments based on carbon budgets

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Abstract

This study assesses Japan's mid-century low-emission pathways using both national and global integrated assessment models in the common mitigation scenario framework, based on the carbon budgets corresponding to the global 2 °C goal. We examine high and low budgets, equal to global cumulative 1600 and 1000 Gt-CO₂ (2011–2100) for global models, and 36 and 31 Gt-CO₂ (2011–2050) in Japan for national models, based on the cost-effectiveness allocation performed by the global models. The impacts of near-term policy assumption, including the implementation and enhancement of the 2030 target of the nationally determined contribution (NDC), are also considered. Our estimates show that the low budget scenarios require a 75% reduction of CO₂ emissions by 2050 below the 2010 level, which is nearly the same as Japan's governmental 2050 goal of reducing greenhouse gas emissions by 80%. With regard to near-term actions, Japan's 2030 target included in the NDC is on track to meet the high budget scenario, whereas it is falling short for the low budget scenario, which would require emission reductions immediately after 2020. Whereas models differ in the type of energy source on which they foresee Japan basing its decarbonization process (e.g., nuclear- or variable renewable energy-dependent), the large-scale deployment of low-carbon energy (nuclear, renewable, and carbon capture and storage) is shared across most models in both the high and low budget scenarios. By 2050, low-carbon energy represents 44–54% of primary energy and 86–97% of electricity supply in the high and low budget scenarios, respectively.

Keywords Carbon budget · Integrated assessment model · Mitigation · Nationally determined contribution · Paris agreement

1 Introduction

The Paris Agreement sets a goal to limit the average global temperature increase to well below 2 °C and to pursue efforts to limit the rise to 1.5 °C above pre-industrial levels. However, according to several studies that have been performed using integrated assessment models

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(IAMs), the collection of greenhouse gas (GHG) emissions implied by the nationally determined contributions (NDCs) is not on track with the optimal pathways toward the 2 °C goal (Rogelj et al. 2016; van Soest et al. 2017b; Vandyck et al. 2016). In particular, Fujimori et al. (2016a) emphasize the effectiveness of the review and revision of current NDCs in Asian countries. In addition, since the Paris Agreement parties are encouraged to formulate long-term low-emission development strategies, some parties have already submitted their mid-century strategies, including the emission reduction target by 2050. Some national and regional IAMs have been utilized to assess the NDCs and national mid-century pathways (Iyer et al. 2017; Pye et al. 2017).

Japan was the sixth-largest emitter of GHGs in 2016, accounting for about 3% of global emissions, with about 88% of national GHG emissions being CO₂ (Olivier et al. 2017). Japan's energy and climate policies were reformed after the nuclear accident in 2011 (see International Energy Agency 2016 for more detail), and Japan has set its NDC target to a GHG emissions reduction of 26% below the 2013 level by 2030, with the long-term goal of an 80% GHG emissions reduction by 2050. National IAMs have assessed the ambition of these national goals (Akimoto et al. 2015; Kuramochi et al. 2017; Masui et al. 2014; Sano et al. 2016), and some of them have explored the feasibility of enhancing this ambition (Oshiro et al. 2017). Sugiyama et al. (2019) employed multiple Japanese IAMs and explored the sectoral mitigation challenges to achieve the long-term decarbonization goal in Japan. These exercises are useful in that they are based on a bottom-up analysis that considers the national context; however, they are generally performed based on the national target expressed as an annual emission reduction. Thus, their implications for the national decarbonization strategy in the context of the global climate goals of the Paris Agreement are still unclear.

Given the country's share of the global GHG emissions, several global IAMs include Japan as one individual region, and these have explored the level of national emissions that would correspond to the global 2 °C goal (Akimoto et al. 2010; Fujimori et al. 2016b; Luderer et al. 2012; van Ruijven et al. 2012; van Sluisveld et al. 2013). Previously, the Asian Modeling Exercise provided the implications for national mid-century emissions pathways for Asian countries, including Japan, based on multi-model intercomparison. Calvin et al. (2012) shows the range of CO₂ emissions in Japan among the different IAMs. However, very stringent mitigation scenarios, such as those implied by the well-below 2 °C goal, were not considered. More recently, van Soest et al. (2017a) assessed the emission pathways in 11 major economies, including Japan, using global models, and indicated that the national emission pathways estimated vary significantly across models. Aldy et al. (2016) explored economic impacts of the NDCs in the seven major economies, including Japan, by using multiple global models, and indicated that economic impact varies among models. Although the results of these studies are useful to gain an understanding of the uncertainties in national low-emission pathways corresponding to the global mitigation target, it is necessary to study their impact on national energy system and mitigation costs more explicitly in order to inform national mid-century strategy in the context of the Paris Agreement.

On the other hand, the national scenario assessments have been conducted based on frameworks that did not consider the harmonization between national and global models. In this study, we bridge the gap by assessing mid-century low-emission pathways in Japan, linking the scenarios from multiple global and national IAMs in a common scenario framework, with the aim to inform the national mid-century strategy in the context of the global 2 °C goal. The long-term carbon budgets were used as a boundary condition to link the scenarios derived from national models with those of global models so that the consistency between the

national emission pathways and the global climate goal was considered. The most recent national policies in Japan, including the implementation of the NDC and other related policies on energy mix, were also taken into consideration so as to inform the global stocktake procedure. In addition, we explored the implications of mid-century national mitigation strategies in the context of the long-term climate goals mentioned in the Paris Agreement.

2 Methods

2.1 Models

Seven global IAMs and two national IAMs covered by the CD-LINKS¹ project were included in this study (Electronic Supplementary Material [ESM] Table S1). Although there are several national models in Japan, two models, namely AIM/Enduse[Japan] (Oshiro and Masui 2015) and DNE21+ (Akimoto et al. 2010; RITE 2015) were selected in this study because of their time horizons corresponding to the mid-century pathways and experiences in the international model intercomparison project that focused both on the NDC and the national 2050 target in Japan (Akimoto et al. 2015; Spencer et al. 2015). For the global models, namely AIM/CGE (Fujimori et al. 2017a, b), COPPE-COFFEE (Rochedo 2016), DNE21+, GEM-E3 (Capros et al. 2014; E3MLab 2017), IMAGE (Stehfest et al. 2014; van Vuuren et al. 2017), POLES (Keramidas et al. 2017), and REMIND-MAGPIE (Kriegler et al. 2017), we included as many models as possible so as to consider uncertainties in the national mid-century low-emission pathways in the context of the 2 °C goal. Whereas this study focuses mainly on the emission pathways by 2050 in Japan, the global models cover the second half of this century to assess the carbon budget associated with the 2 °C goal (see Section 2.2). The models differ in terms of model type and solution algorithm as well as regional coverage. As shown in ESM Table S1, most intertemporal models simply considered the budgets constraint, while the recursive dynamic models assumed emission or carbon tax trajectory over time. Because DNE21+ performs both national and global analyses under different scenario protocols, the model versions are referred to as DNE21+ (national) and DNE21+ (global) throughout this study.

2.2 Carbon budgets

In this study, we used the carbon budget as the boundary condition to link the scenarios of global and national models in accordance with the modeling protocol of CD-LINKS. The global models used global carbon budgets of 1600 and 1000 Gt-CO₂, including agriculture, forestry, and other land use (AFOLU) emissions between 2011 and 2100, which roughly correspond to a 50 and 67% chance, respectively, of keeping the temperature increase below 2 °C by the end of this century (Luderer et al. 2018). The national models used the national budgets between 2011 and 2050, which were set at 36 and 31 Gt-CO₂, respectively, based on the global models results under a cost-effective allocation and the discourse between the national and global modeling teams. Because most of CO₂ was emitted by energy and industrial processes in Japan (United Nations Framework

¹ CD-LINKS: Linking Climate and Development Policies—Leveraging International Networks and Knowledge Sharing (www.cd-links.org)

Convention on Climate Change 2017), the national budgets include CO₂ emissions from these sectors. Although non-CO₂ emissions are not constrained explicitly, CO₂ equivalent prices are implemented for the emissions of non-CO₂ gases as well. It should be noted that carbon budgets in this study are derived from only the global models' result and, therefore, they are not associated with specific climate policies in Japan or with the consequences of international negotiations. Also, the national budgets may vary with different effort-sharing schemes. Although this study does not focus on these areas in detail, Van den Berg et al. (2019) do explore extensively national budgets and pathways under several effort-sharing schemes.

2.3 Scenario design

In order to incorporate the most recent national policies, including the NDC, and the global long-term mitigation goal in the context of the Paris Agreement, seven scenarios were examined based on the near-term emissions conditions and the long-term high and low budgets (Table 1).

For near-term policy dimensions, a reference scenario without any explicit climate policies (NoPOL) and following two policy scenarios were examined. National Policies implemented (NPi) took the current energy and climate policies until 2020 into consideration, whereas this scenario has no explicit emission constraints in the near-term. NDC considered policies additional to those represented in NPi, which reflect policies or targets included in Japan's NDC until 2030 as well as the emissions reduction target by 2030. In the NPi and NDC scenarios, there was a protocol specifying that the rates of emissions reductions relative to the NoPOL or NPi scenarios in 2030 should be kept constant after 2030.

For the technological conditions, the most recent national energy and climate policies were considered based on the CD-LINKS climate policy database (NewClimate Institute et al. 2016). For example, in the NDC and NDC1600/1000 scenarios, most models included the national 2030 target, which is to increase the share of nuclear and renewable energy to 20–22% and 22–24% of total electricity generation, respectively. However, given the uncertainties of policy perspectives, especially those for nuclear power in Japan, the assumptions on the technological conditions were not fully harmonized so as to be able to consider several options and possibilities for energy system transformation. The detailed assumptions by the models are summarized in ESM Table S3. Assumptions regarding socio-economic conditions were also not fully harmonized in order to reflect both structural and parametric uncertainties to a range of the results. For example, the assumed population and economic growth differed across

Table 1 Scenario design based on the near-term emissions conditions and the long-term budgets

Near-term policies	Long-term CO ₂ budgets		
	None	High	Low
No policy	NoPOL	—	—
NPi	NPi	NPi1600	NPi1000
NDC	NDC	NDC1600	NDC1000

NoPOL Reference scenario without any explicit climate policies, *NPi* National Policies implemented, *NDC* nationally determined contribution

The high and low budgets are equal to 1600 and 1000 Gt-CO₂, respectively, between 2011 and 2100 for the global models, and between 36 and 31 Gt-CO₂, respectively, between 2011 and 2050 for the national models

models. A large gap was observed between the national and global models because the global models refer to other scenario frameworks, such as shared socio-economic pathways, while national models refer to the government's official economic prospects, which are more optimistic for economic growth (ESM Fig. S1 Table S4).

3 Results

3.1 Emissions

The cumulative CO₂ emissions over the periods of 2011–2050 and 2051–2100 among the models are shown on Fig. 1. With regard to the global models, although the median across the models is almost consistent with the national budgets, cumulative emissions between 2011 and 2050 vary to some extent across the models. In addition, the range of cumulative emissions by 2050 also differs by the different near-term policies. For example, cumulative emissions in the NDC1000 scenario were found to exceed the carbon budget in some models; therefore, this scenario is characterized by a deeper emission reduction in the second half of this century, and even the net removal of CO₂ between 2051 and 2100. A discussion of the effort-sharing schemes in the global models and an assessment of the longer-term pathways are beyond the scope of this study; however, it should be noted that uncertainties remain in the number of national budgets.

Although the trajectories after 2050 are not the main focus of this study, the global 1000 Gt-CO₂ budgets scenario suggests that cumulative emissions in Japan in the second half of this century need to be nearly zero. In particular, if near-term emissions follow the level of the NDC, the net removal of CO₂ would be required in the second-half of the century in the global 1000 Gt-CO₂ scenario, which is equivalent to about 4.1 Gt-CO₂ (median), because cumulative emissions in the first half of the century exceed the national budget by 2100.

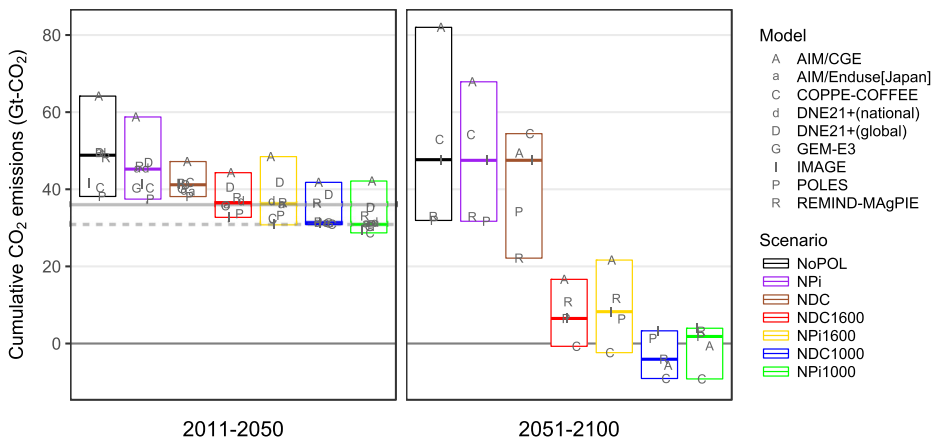


Fig. 1 Cumulative CO₂ emissions from energy and industrial processes over the period of 2011–2050 and 2051–2100 in Japan. Boxes indicate the full ranges, while the horizontal line segments show the median values of global model results. The horizontal lines (solid and dashed) represent high and low budgets (36 and 31 Gt-CO₂), respectively. *NoPOL* Reference scenario without any explicit climate policies, *NPi* National Policies implemented, *NDC* nationally determined contribution, *1600*, *1000* global carbon budgets of 1600 and 1000 Gt-CO₂, respectively

The CO₂ emissions pathways in Japan over the period of 2010–2050, and their ranges across the models in 2030 and 2050, are depicted in Fig. 2. The figures for total GHG emissions and detailed results can be found in ESM Fig. S2, Table S5 and S6. Because the trend in the emission reduction from 2010 is broadly consistent between CO₂ and GHGs, we mainly focus on CO₂ emissions in this section. CO₂ emissions in the NoPOL and NPi scenarios remain almost stable, and their reductions in 2050 from the 2010 level are 8% (median; full range – 17 to 33%) and 14% (full range – 4 to 34%), respectively. In the NDC scenario, CO₂ emissions continue to fall after 2030 in most models, decreasing by 29% (full range 10–45%) in 2050 with respect to the 2010 level.

Additional mitigation efforts are required to meet the carbon budget that corresponds to the global climate objective of keeping the temperature rise below 2 °C. To meet the high budget, the median CO₂ emission reduction reaches 61% below the 2010 level (full range 35–74%) by 2050. In these scenarios the emissions of total GHGs also fall by 63% (median 33–76%) (see ESM Fig. S2). The low budget scenarios (both NDC100 and NPi1000), as well as the high budget scenarios, require a substantial emission reduction, which is equivalent to a 75% (full range 47–89%) reduction by 2050 below the 2010 level. As shown in ESM Fig. S2, a similar trend is observed in the reduction of total GHG emissions, where the median reduction in 2050 is 73% (range 45–91%) below the 2010 level. This reduction is broadly similar to the national long-term goal in Japan to reduce GHG emissions by 80%.²

For the sectoral CO₂ emissions, while emissions from the energy demand sectors vary across models, all models show rapid and significant emissions reduction in the energy supply sector in 2050 (Fig. 2, bottom, ESM Fig. S3). In particular, energy supply is nearly decarbonized by 2050 in the low budget scenarios (median 93–97% reduction below 2010). In the energy demand sectors, the median CO₂ emissions in the low budget scenarios are reduced by 59–64% by 2050 relative to 2010, while those in the high budget scenarios are halved in this period.

With regard to the near-term policy dimension, in the high budget scenarios, the median CO₂ emissions in 2030 in the NPi1600 scenario (– 24% below 2010) are almost identical to those in the NDC1600 scenario (– 23% below 2010), suggesting that Japan's NDC is broadly on track to meet the emission pathway corresponding to the global 1600 Gt-CO₂ budget. In contrast, given the stringency of the carbon budget in the low budget scenarios, median CO₂ emissions in the NPi1000 scenario fall by 34% (full range 14–39%) by 2030, whereas the NDC1000 scenarios show a 23% reduction. Although all models explored the pathways to meet the low budget with no additional effort beyond the NDC by 2030, these pathways involve a rapid emission reduction after 2030. Figure 3 shows that the average annual changes in CO₂ emissions in the NDC1000 scenario represent – 5.2 and – 6.1% (median) over the periods of 2030–2040 and 2040–2050, respectively, whereas in the NPi1000 scenario, the corresponding figures are – 4.4 and – 4.7%, respectively. Consequently, the median CO₂ emissions in the NDC1000 scenario reach the same extent as those in the NPi1000 scenario by 2035, and are lower after 2040 (Fig. 2). For the last half-century, Japan's economy has experienced such drastic changes only in the oil crisis in the 1970s and 1980s and in the global economic recession at the end of 2000.

² Because Japan's long-term goal does not specify any base-year, these numbers are not directly comparable. According to UNFCCC (2017), GHG emissions (without land use, land-use change, and forestry (LULUCF)) in Japan accounted for about 1.27, 1.39, and 1.30 Gt-CO₂-equivalents in 1990, 2005, and 2010, respectively.

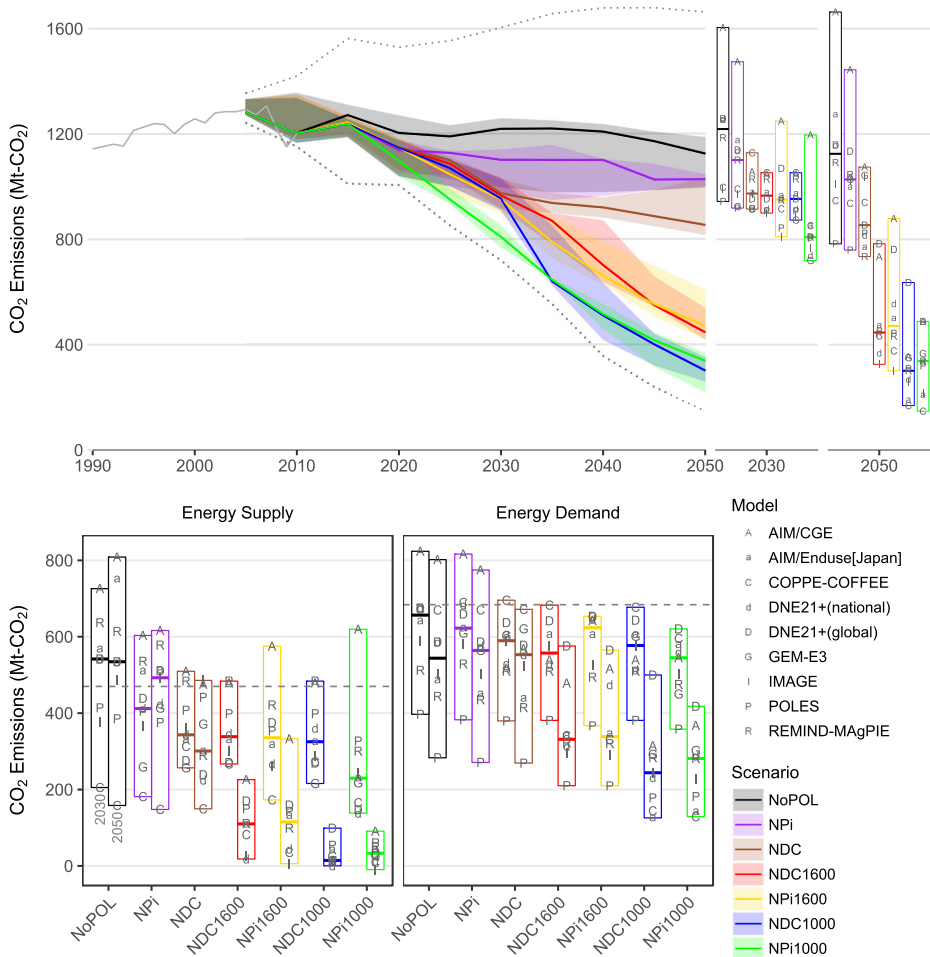


Fig. 2 Top left panel shows the pathways of annual CO₂ emissions from energy and industrial processes in Japan for the various scenarios. Lines indicate the median values, and ranges indicate the first to third quartiles of the results. The gray line indicates the historical emissions trajectory from 1990 taken from UNFCCC (2017). The dotted line shows the full range of the results. Top, right panel shows the range of annual CO₂ emissions in 2030 and 2050. Boxes indicate the full range, and the horizontal line segments show the median. Plots indicate the results of each model. Bottom panels show the range of sectoral direct CO₂ emissions in 2030 and 2050. The dashed line shows the 2010 level

3.2 Energy system

In both the high and low budget scenarios, upscaling of low-carbon energies, including nuclear, renewable, and carbon capture and storage (CCS), is a key mitigation option for the most models (Fig. 4, top, ESM Fig. S4). While the share of low-carbon energy accounts for about 10 and 6% of the total primary energy supply in 2010 and 2015, respectively, the median share in 2050 increases to 44% (full range 25–61%) and 54% (full range 42–75%) in the high and low budgets scenarios, respectively. In addition, the share of low-carbon energy has to be approximately tripled over the period of 2030–2050 both in the high and low budget scenarios. A more rapid increase is required if the emissions by 2030 follow the NDC. To achieve this

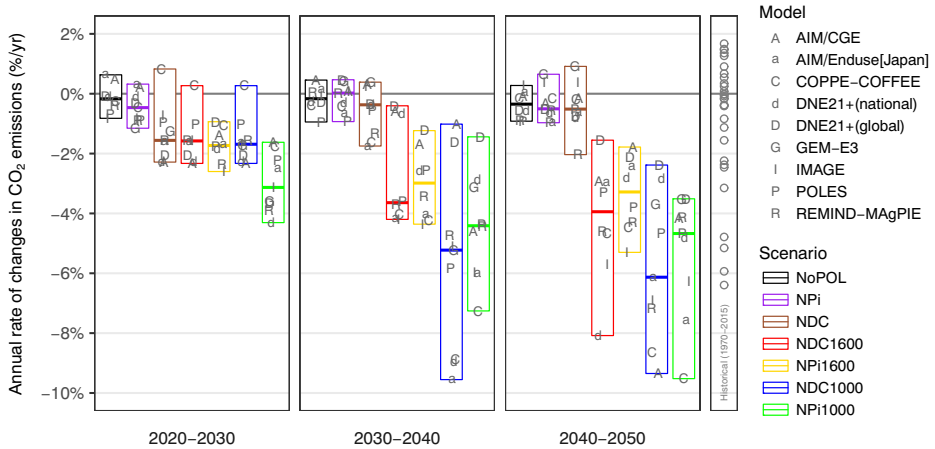


Fig. 3 Average annual rate of changes in CO₂ emissions from energy and industrial processes by decade in Japan. The empty circles shown in the right panel indicate the historical annual changes between 1970 and 2015 taken from European Commission's Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL) (2016). Changes of > 2% per year are not shown

drastic emission reductions in the energy supply sector, about 86% (full range 72–100%) and 97% (full range 77–100%) of electricity comes from low-carbon energy sources by 2050 in the high and low budget scenarios, respectively. Especially in the low budget scenarios, electricity is nearly decarbonized by 2050 and, in some scenarios, net CO₂ emissions from electricity become negative due to the deployment of bioenergy with CCS (BECCS). With regard to the near-term, more than 60% of electricity comes from low-carbon sources in 2030 in the NPi1000 scenario, without depending on CCS (the share of each low-carbon energy can be found in ESM Figs. S5, S6).

The development of the shares of various energy sources in the primary energy supply and electricity generation in the high and low budget scenarios over the period of 2010–2050 is shown in Fig. 4 (bottom). In both the high and low budget scenarios, fossil fuel without CCS is substituted by low-carbon energies over time; however, the share of the low-carbon energy source varies among all models, both national and global. The share of nuclear and renewables in primary energy in 2050 ranges from 5 to 23% and from 14 to 39%, respectively, in the NDC1000 scenario (see ESM Table S7 for more detail). Some models are characterized by the conservative assumption of nuclear and CCS accounting for ≤ 20% of the primary energy supply, together with a dependency on renewables. In contrast, other models depend largely on nuclear and/or CCS, while the share of renewables in the primary energy supply remains at < 20% in 2050. The detailed results on the low-carbon energy share can be found in ESM Tables S7 and S8. The range of the share of CCS is relatively wider compared with other energy sources in 2050, reflecting the different assumptions among models.

The change in the energy demand from 2010 onward and the share of low-carbon carriers are summarized in Fig. 5 and ESM Fig. S7–S9. Although the final energy consumption varies greatly across the models, the median drops to 20 and 26% in the high and low budget scenarios, respectively, by 2050. In particular, a large-scale reduction in energy demand is observed in transportation sector by 2050 (median – 41% below 2010 in low budget scenarios). In addition, the share of low-carbon carriers, such as renewables, electricity, hydrogen, and heat, is increased with the more stringent carbon budget in 2050. In the low budget scenarios, this share exceeds half of

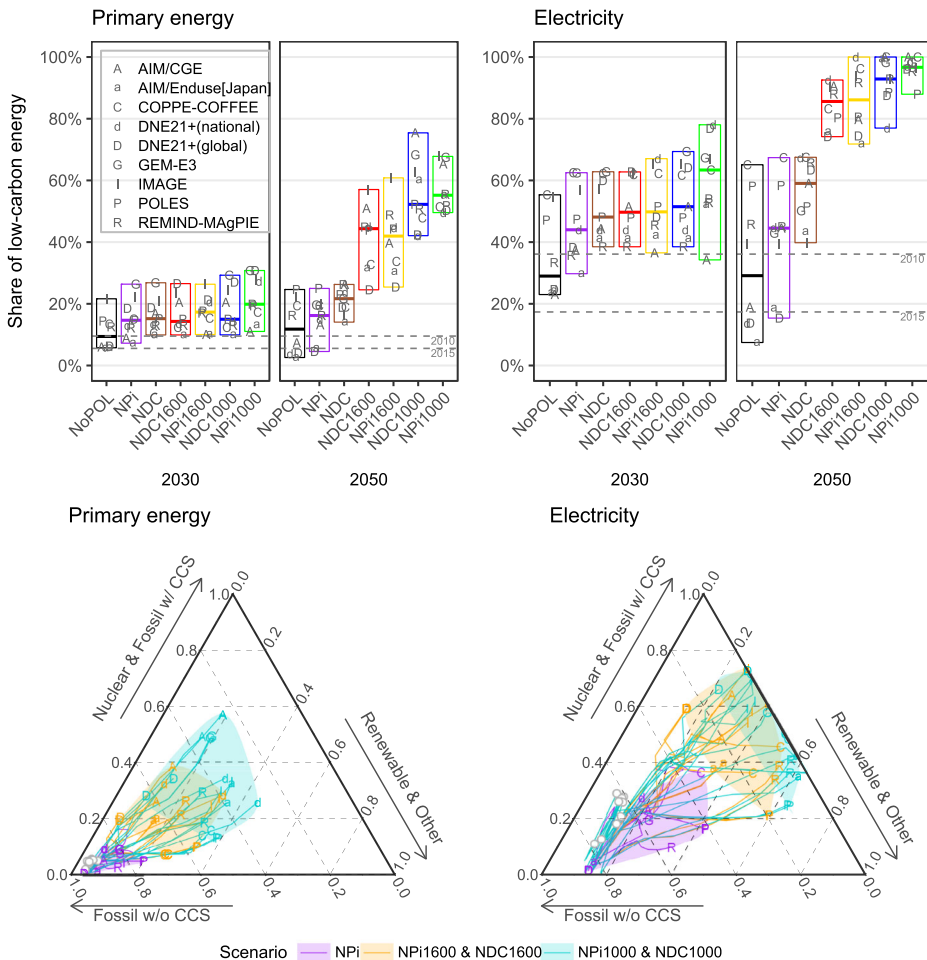


Fig. 4 Top panels show upscaling of low-carbon energies in the primary energy supply and electricity generation in 2030 and 2050 in Japan. Low-carbon energies include nuclear, renewables, carbon capture and storage (CCS), and imported hydrogen. The dashed line shows the historical data in 2010 and 2015 taken from the International Energy Agency (2017). Bottom panels show the development of the share of energy sources over the period of 2010–2050. Empty circles indicate the share in 2010. Model markers and the shaded areas show the share in 2050

the final energy consumption by 2050. The buildings sector is characterized by a large-scale deployment of low-carbon energies; especially in the low budget scenarios this accounts for almost 80% by 2050, while energy demand reduction is moderate in this sector.

3.3 Mitigation costs

The relationship between carbon prices and emission reductions in 2050 relative to those in 2010, and the net present value (NPV) of mitigation costs expressed as a fraction of the baseline gross domestic product (GDP) for the period of 2021–2050 are shown in Fig. 6. Although carbon prices of each model should not be directly compared because the level of emission reduction in 2050 is different depending on the model, the stringency of the carbon

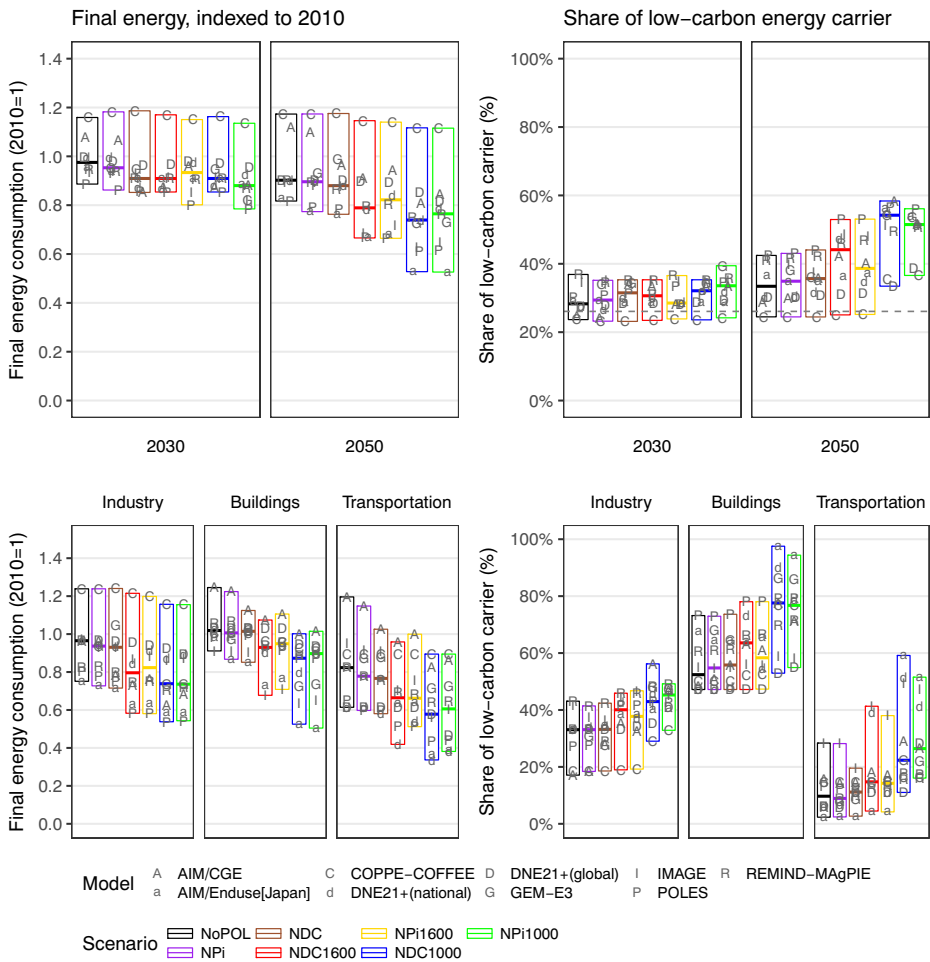


Fig. 5 Range of the change in final energy consumption relative to 2010 (top, left) and the share of low-carbon energy carriers in the total final energy supply (top, right) in Japan. Low-carbon energy carriers include electricity, heat, and hydrogen and renewables (biomass, solar, and geothermal) in accordance with the definition in the Intergovernmental Panel on Climate Change (IPCC) (2014). Bottom panels show the change in final energy consumption indexed to the 2010 level and share of low-carbon energy carriers by sector in 2050

budget has a large impact on the level of the carbon price for all models. In the high budget scenarios, the median carbon price is projected to be 110 US\$/t-CO₂ by 2050 (full range 65–261 US\$/t-CO₂) and 141 US\$/t-CO₂ (full range: 36–431 US\$/t-CO₂) in the NPI1600 and NDC1600 scenarios, respectively. Although cumulative mitigation costs (NPV) over the period 2021–2050 are also not directly comparable as the models report different cost indicators, they range from 0.1 to 2.0% of the baseline GDP in the high budget scenarios.

In contrast, to meet the more stringent carbon budget, the low budget scenarios require an additional effort compared with the NDC and the high budget scenarios. The median carbon price in the NDC1000 scenario rises to 497 US\$/t-CO₂ (full range 133–2093 US\$/t-CO₂) in 2050, while in the NPI1000 scenario it represents 376 US\$/t-CO₂ (full range 151–1073 US\$/t-CO₂). NPV mitigation cost in the low budget scenarios also becomes higher than the high

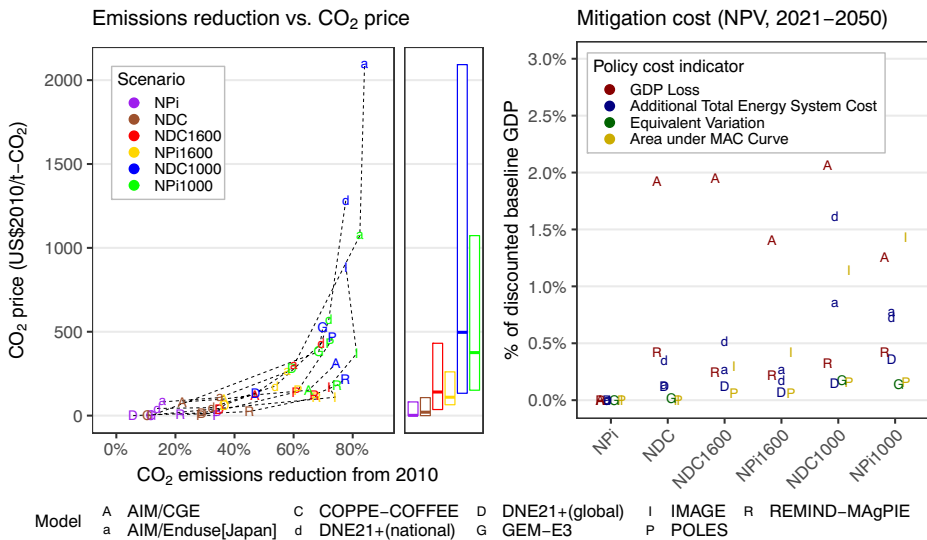


Fig. 6 Left panel shows the reduction of CO₂ emissions relative to 2010 versus the price of carbon in 2050 across the various scenarios, and the range of the price of carbon in Japan. Right panel shows the range of the net present value (NPV) mitigation costs accumulated over the period of 2021–2050 relative to the NPi scenario as a fraction of baseline gross national product (GDP), discounted at the rate of 5%. Mitigation costs indicators are different among models

budget scenarios for most models, although the full range is similar with the high budget scenarios (0.1–2.1%).

With regard to carbon price, a large gap is observed, especially among the national and global models (ESM Fig. S10a). One plausible reason for this gap is that the national models result in a deeper emissions reduction in 2050, especially for AIM/Enduse[Japan], and they assume larger economic growth than the global models. In addition, the national model considers regional specific barriers, such as constraints on electricity interconnections across sub-regions in Japan for AIM/Enduse[Japan], which would exacerbate the challenge to integrate variable renewable energies (VREs). It should also be noted that cumulative mitigation costs for some global models, such as DNE21+ (global), IMAGE, and REMIND-MagPIE, in the NDC scenarios are smaller than those in the NPi scenarios, especially in the low budget scenarios. This is in contrast to the national models and is generally associated with the higher carbon budgets in the NDC scenarios between 2011 and 2050, which are compensated for in the second half of this century in these global models (Fig. 1). Whereas the differences in the carbon budget between the NDC and NPi scenarios are moderate for IMAGE, this model shows a large difference in the annual mitigation costs in 2030 between the NDC1000 and NPi1000 (ESM Fig. S10b), thus the cumulative cost in NPi1000 is still higher compared with the NDC1000.

4 Discussion and conclusion

In this study we explored the low-emission pathways up to 2050 in Japan based on the stringent carbon budgets suggested by the 2 °C goal and the latest national climate policies and subsequently identified the following implications for the national mid-century strategies. As shown in Fig. 2, the NDC policies are consistent with the high budget scenario,

effectively keeping the country on track. The low budget scenarios suggest that the national 2050 goal to reduce GHG emissions by 80% can be considered to be an effective milestone in the context of the global 2 °C goal because the level of emissions reduction in 2050 in these scenarios is almost consistent with the national 2050 goal. Nevertheless, the mitigation effort for low budget scenarios would be significantly too weak without additional mitigation action beyond the NDC after 2030. For most models, decarbonization of the energy supply is observed in 2050 in the low budget scenarios. In terms of energy systems, both the national and global models suggest that a transformation of the energy system is a key aspect of all scenarios. However, the energy sources mainly used for decarbonization differ across models: nuclear, CCS, or renewable energies. Mitigation costs are generally increased in the scenarios with stringent carbon budgets for most models, whereas there is a wide variety among models, especially between the national and global models.

However, the following factors should be considered carefully. First, the emission pathways of the low budget scenarios entail huge challenges for achieving the rapid reduction of and associated transformation in the energy system. For example, the rate of emissions reduction between 2030 and 2050 in the NDC1000 scenario corresponds to about 6% per year. Over the last half-century, Japan's economy has only experienced such drastic changes during the oil crisis and the global economic recession. It should also be noted that increasing the mitigation effort in 2030 would also be challenging, requiring the integration of more VREs and the restarting of nuclear power plants. For example, the NP1000 scenario would require an increase in the share of low-carbon electricity generation to more than 60% by 2030, without depending on CCS.

Second, there are still large uncertainties in the national budgets which were derived from the global models as shown in Fig. 1. In addition, the range of the carbon budget would be wider when other effort-sharing schemes are considered, such as those based on equity and capability; for example, national budgets result in 6–39 Gt-CO₂ over the period of 2011–2050, with a global carbon budget of 1000 Gt-CO₂ under the various effort-sharing approaches (van den Berg et al. 2019). Also, emission pathways by 2050 are associated with those in the second half of this century. Although this study mainly focused on the national scenarios by 2050, it would also be useful to explore the national pathways in the second half of this century when considering the possibility of large-scale negative emissions and the impact of emissions overshoot by 2050.

Third, in some indicators a gap between the national and global models is observed. For example, the carbon prices in the national models tend to be higher than those in the global models. One reason for these differences would be derived from the representation of specific circumstances in Japan, such as limitations in integrating VREs. This gap emphasizes the importance of the further development of national model exercises, not only by using bottom-up models with fixed demand but also top-down models, such as AIM/CGE[Japan] and DEARS, that incorporate specific regional circumstances, and the utilization of these experiences in the assessment of global models.

Fourth, to meet the high and low budgets, it is necessary to transform the energy system as shown in most models' results, while taking into account the levels of technological uncertainty in Japan. In this study, the share of renewables, nuclear, and fossil fuel CCS in primary energy and electricity generation vary significantly across the models, reflecting technological uncertainties as well as the model structure (Fig. 4). This variation suggests that there are various options for energy system transformation in Japan that correspond to the global 2 °C

goal. Nevertheless, several barriers remain, such as the limited potential of carbon sequestration, the integration of VREs, the costs of these technologies, and the uncertainties regarding nuclear power availability.

To explore the national development pathways corresponding to the global climate goal, it would be effective to link the scenarios from national and global IAMs in the common framework based on a carbon budget approach. In the context of the implementation of the Paris Agreement, these exercises would be meaningful not only for developing the national low-emission strategy but also for developing the global stocktake procedure.

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Compliance with ethical standards

Disclaimer The views expressed are purely those of the writer and may not in any circumstances be regarded as stating an official position of the European Commission.

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